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Some observations on the composition of fogs

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K. H. Stewart

(Meteorological Office)

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

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1. Introduction

A knowledge of the number of droplets of different sizes in a fog is essential to the understanding of many of the physical processes involved in its formation, persistence and dispersal. It was therefore decided to include the measurement of drop size distribution in the general programme of research on fog being carried out at Cardington. It was at first thought that the measurements could be made relatively simply, but unexpected difficulties arose and the problem of devising satisfactory measuring techniques was transferred to Kew Observatory. The techniques devised at Kew are still under development and do not yet give drop size distributions in great detail, but the results already obtained differ so much from previous ideas on the composition of fog as to seem worth reporting.

2. Observations with a cascade impactor

Samples of many fogs were taken with the "cascade impactor" described by May (1945). The fog drops were caught on microscope slides coated with Napthol Green B in gelatine (Wootten, 1955) and the resulting ring-shaped stains were counted and sized under a microscope. Fuller details of the sampling technique are given in Appendix I.

The results are summarized in table I which gives, for each size-range of drops, the sum of the cross-sectional areas (πr^2) of all the drops in unit volume of air whose diameters lie within the size-range. This quantity is denoted by S_i (for the i th size-range); its dimensions are area/volume and it is conveniently expressed in units of Km^{-1}. It is convenient to use S_i rather than the number (n_i) or mass (m_i) of drops of given sizes per unit volume because S_i is more closely related to the optical properties studied in the present work. In particular, the contribution of the drops of the i th size-range to the optical attenuation coefficient, σ_i, is given by $\sigma_i = K_i S_i$ where K_i is the appropriate value of the "scattering area coefficient" K calculated by Houghton and Chalker (1949) and others as a function of r/λ (r = radius of drop, λ = wavelength of light). For drops larger than about 5 μ in diameter, the only ones of importance in table I, K is found to be equal to 2.0. The contribution of all the drops of a sample to the attenuation coefficient is therefore given by $\sigma_d = \Sigma_i S_i$ which is included in table I.

The values of σ_d are to be compared with observed values of attenuation coefficient, σ, given in the next column of table I. Most of the values of σ were derived from observations of visibility, V, by Koschmieder's formula $\sigma V = 3.91$, but others were obtained, independently of visibility observations or Koschmieder's formula, from measurements of attenuation made with a Gold or photoelectric visibility meter. (Despite their names, these instruments measure attenuation not "visibility").

It will be seen that there are enormous discrepancies between the values of σ_d and σ . A part of the discrepancy can be attributed to the effect of smoke particles on the attenuation, but rough estimates of their contribution (σ_s) to the attenuation coefficient can be made from the measurements of smoke pollution made with the Owens automatic pollution recorder and it will be seen that in most of the cases tabulated σ_s can account for only a small fraction of the discrepancy.

A careful investigation of the operation of the cascade impactor (see Appendix I) showed that it was very unreliable as a sampler of water drops smaller than about 10μ in diameter. Many of these drops seem to be lost by evaporation in their passage through the impactor, the fraction lost increasing rapidly with decreasing size. For drops between 10 and 20μ the impactor seems reasonably accurate (though random errors of sampling lead to an uncertainty factor of the order of 2 in the true drop concentrations) but for larger drops sampling errors due to inertia effects begin to be important. These are rather worse in the conditions of fog sampling (when a quite small volume of air has to be sampled from an almost calm atmosphere) than in the conditions in which the impactor was originally tested (with relatively large volumes drawn from a wind blowing into the instrument), but for drops up to 50μ the average losses probably do not exceed 75 per cent.

We conclude, therefore, that the results of table I can be taken as approximately correct for the size range 10-20μ ; for sizes of 5-10μ and 20-50μ the impactor results give some qualitative indication of the presence or absence of drops, while drops smaller than 5μ or larger than 50μ may be missed entirely.

An independent rough estimate of the numbers of drops larger than about 10μ was made on several occasions by the very simple method of exposing Napthol Green-coated slides face upwards on the ground for a few minutes and then examining the stains produced by drops that had settled under gravity on to the slides. The numbers of drops of different sizes per unit volume of air were calculated from the numbers of stains per unit area of slide, the times of exposure and the theoretical terminal velocity of the drops. The results are included in table I. It will be seen that these "sedimentation" samples agree tolerably well with simultaneous impactor samples in the 10-20μ size range but contain fewer smaller drops and more larger ones. Presumably drops smaller than 10μ are prevented from settling by local eddies or evaporate on contact with the slide, without leaving a stain, while larger drops are sampled correctly by the sedimentation method and the excess over impactor results above 20μ is due to inertial losses in the impactor. The chief value of the sedimentation results, however, is that they indicate that in most of the fogs sampled there were no appreciable numbers of drops larger than 50μ and relatively few between 20 and 50μ , so that the inertial losses of the impactor for large drops affect only the upper tail of the drop size distributions of Kew fogs and are certainly not the prime cause of the wide discrepancies between σ and σ_d in most cases of table I. It is clear that the discrepancies must be attributed to the presence of large numbers of drops too small for the impactor to sample properly, i.e., below 5-10μ .

The results of table I have been considered in the light of these ideas on the performance of the impactor. The samples fall roughly into two classes; in the denser fogs (visibility less than 100 metres) there are quite large numbers of drops, mostly 5μ and above, enough to account for about 1/5 of the observed attenuation coefficient, but in the thinner fogs (with visibilities 100-400 metres) the numbers of drops in the samples are extremely small and never account for more than 1/20 of the attenuation. In these thinner fogs it seems very unlikely, even making maximum allowance for evaporation losses in the impactor, that drops bigger than 5μ can be numerous enough to contribute more than a very small fraction of the attenuation; the bulk of the attenuation must be due to smaller drops, possibly to drops so small that they should be classed as "nuclei" rather than as "true" water drops.

In the thicker fogs it is just possible, by supposing rather large inertial and evaporative losses in the impactor, to explain the observed attenuation in terms of a distribution of "large" drops ($> 5\mu$), but it seems more likely that in these fogs too, small drops below 5μ contribute an important part, probably more than half, of the total attenuation.

The liquid water contents suggested by the data in table I are also of interest. In the thicker fogs the values calculated from the impactor samples range from about 0.1 gm/m^3 down to 0.01 gm/m^3. These values have, of course, to be increased to allow for the relatively small number of large drops lost by inertial effects and the large number of small drops lost by evaporation. The former can be estimated roughly from the sedimentation measurements, and an upper limit to the latter can be found from the attenuation attributed to the small drops. The result is that the measured water content should be increased by a factor of roughly 2, so that we obtain a maximum liquid water content of about 0.2 gm/m^3 for Kew fogs, with 0.1 gm/m^3 as a typical value for fogs of about 30 metres visibility. In the thinner fogs the measured values are extremely low, from nil up to about 0.001 gm/m^3. An upper limit for the contribution from small drops lost by evaporation can again be found from the attenuation; it is about 0.05 gm/m^3 for a fog with 100 metres visibility, but the actual value may be well below this limit. These liquid water contents are at least ten times smaller than the much-quoted values given by Houghton and Radford (1938); their figures referred to coastal fog and cloud rather than to the suburban radiation fogs sampled at Kew.

The cascade impactor results are obviously very unsatisfactory and the deductions drawn from them must be regarded as speculative. In view of the idea that drops smaller than 5μ, and perhaps even those below 1μ, are an important component of fogs it seemed unlikely that the cascade impactor, or indeed any other impaction device, could be made to give satisfactory results and other methods of studying fogs were investigated.

3. Optical methods of studying fog

The idea of obtaining information about the drop size distribution in fog from optical measurements (including those using infra-red radiation) is attractive because it is possible to make measurements in almost undisturbed fog, giving average values over quite large volumes. The disadvantage of optical methods is that there is no property which varies in a simple manner with drop size (over the range encountered in fogs) and it is consequently difficult to determine size distributions uniquely from the optical measurements. Two types of measurement seem to offer the best hope of obtaining useful results. The first is the measurement of attenuation as a function of wavelength; as a very rough approximation the attenuation should be independent of wavelength for short waves but fall to zero for waves longer than the drop diameter, so that measurements at a given wavelength indicate the contribution from drops larger than that length. The more exact dependence of attenuation on drop size and wavelength, as calculated by Johnson and Terrel (1955) is not so simple, and the construction of drop size distributions from attenuation measurements is correspondingly difficult and uncertain. Nevertheless Arnulf, Bricard and Veret (1954) have found fairly close agreement between experimental and theoretical attenuations in natural fogs and Eldridge (1957) has applied the method to the estimation of drop size distributions in cloud on Mount Washington. The range of sizes for which the method is effective is roughly the same as the range of wavelengths employed, so it is desirable to extend the measurements as far into the infra-red as possible.

The second type of measurement is of the fraction of an incident beam scattered at small forward angles. This is an extension of the familiar "corona" method in which a mean size of cloud drops is deduced from the angular position of the first minimum in the scattered light. The corona method fails in most fogs because the spread of drop sizes is so great that no minimum is discernible. By quantitative observations of the intensity of scattered

light as a function of angle a good deal more information about the drop size distribution can be obtained. The relation between drop size and scattered light is again not simple, so that interpretation of the results is difficult and uncertain. The relations are simplest and the discrimination between drops of different sizes best when the drops are large compared with the wavelengths used and when the observations are made at angles of order λ/r, so that fog measurements are best made with visible light and at angles from a fraction of a degree to several degrees.

Both types of optical measurement have been attempted at Kew, using crude forms of apparatus intended to give some idea of the type of result to be expected and so to permit the design of improved measurements. Neither method leads to great experimental difficulties, unless very high accuracy is required, but both lead to the same type of problem in the interpretation of results, the construction of drop size distributions whose optical properties would fit the observed results, and the determination of the limits within which these distributions must lie. (There will always be more than one distribution fitting the data to any required degree of accuracy).

Details of the methods of measurement are given in the appendices. Observations were made in five broad bands of wavelength in the attenuation method and at four angles in the scattering method. In the attenuation method the "sample" was a 40 metre stretch of fog about 4 ft above the lawn at Kew, disturbed only by the apparatus at the two ends of the stretch; in the scattering method the sample was a small volume of fog about 1 cm x 2 cm x 20 cm, 5 ft above the lawn and practically undisturbed by the apparatus. The results are given in table II, expressed as attenuation coefficients (Km^{-1}) for the five wavebands or as angular scattering coefficients (beam candlepower/unit volume for each lumen/unit area in the incident beam) in Km^{-1} for the four angles of observation.

The first stage in finding drop size distributions that would fit these observations is to find the contribution that a drop of any particular size would make to the attenuation or scattering coefficients at the selected wavelengths or angles. This was done by drawing graphs of the coefficients as functions of drop size from the data of Johnson (1955) and of Gumprecht et al (1952), obtained by numerical computations from the Mie theory. The scattering coefficients are given directly by the numerical data, for the four selected angles, for certain values of drop size, but to cover the full range of drop sizes required it was necessary both to interpolate between the data and to extrapolate them to larger sizes (using simple diffraction theory). The curves so obtained are probably accurate enough for use with the present observations but some closer approximation to the full Mie theory may have to be used in the future. The attenuation coefficients given by Johnson for a series of values of drop size and wavelength had to be suitably averaged to allow for the distribution of energy over each of the wavebands for which observations were made.

The curves obtained in this way show the broad features that would be expected. The attenuation produced by drops larger than 12μ diameter is about the same for all the wavebands used; smaller drops give maximum attenuation for wavelengths of about twice their diameter falling to a constant, slightly smaller value for shorter wavelengths and to very small values for larger wavelengths; drops smaller than about 0.5μ affect only the shortest waveband used. The scattering produced by drops smaller than 2μ is approximately constant for all four angles of observation but as the drop size increases the scattered light becomes more and more concentrated at small angles. Both sets of curves contain many minor oscillations, but these would only be important in fogs with remarkably uniform drop size.

/Given

Given the curves of attenuation or scattering coefficients against drop size, we have to find drop size distributions which will give rise to the observed values of the coefficients set out in table II. Since there are only four or five observations to be fitted, it is unlikely that we shall be able to determine distributions in much detail; at best we can hope to estimate about four parameters defining the distribution. The results of table II have therefore been fitted by taking groups of drops of sizes 0-1.25, 1.25-2.5, 2.5-5, 5-10 and 10-20 μ and finding the number in each group required to give a distribution whose attenuation or scattering coefficients would match the observed values. It is, of course, necessary to make some assumption about how the drops are distributed within each of the groups, and the convenient and reasonably plausible assumption made here is that the number of drops, dN, with radius between r and r + dr is given by

$$\frac{dN}{d \log_{10} r} = \frac{C_i}{r^2} \quad \text{or} \quad \frac{dN}{dr} = \frac{C_i}{2.3r^3} \qquad \ldots\ldots (1)$$

where C_i is a constant for the i th size range. The effects of different assumptions about the distribution will be discussed later. From (1) and the curves for attenuation and scattering coefficients as functions of drop size, we can calculate the contribution, for unit value of C_i, which each group would make to the coefficients. These contributions are set out in table III. To find a distribution, then, we have to find sets of values of C_i by which the contributions in table III have to be multiplied in order that the sums of the contributions for each waveband or angle may match the observations. This of course involves solving a set of four or five simultaneous linear equations, with the proviso that negative values of C_i are not allowed. The values of C_i given in table II have, in fact, been found by a process of trial and error, usually intuitive but in some cases a systematic relaxation process.

These values of C_i, together with equation (1), define the distributions which fit the observations, and can readily be converted into mass - or number - distributions if required. The most direct conversion is into the area-distribution used in presenting the cascade impactor results; it can easily be shown from equation (1) that the value of C_i for a given size-range of drops is proportional to the total cross-sectional area of those drops per unit volume of air, i.e., to the quantity S_i used in table I. For a size range whose limits are in the ratio two to one, as in tables I and II, we find $S_i = (\pi \log_{10} 2) C_i$ or, to the accuracy of the present results, $S_i = C_i$. This does not apply, of course, to the smallest size group of the tables, which, if equation (1) applied down to the very small sizes, would contribute an infinite amount to the cross-sectional area. Factors for converting the tabulated C_i values into the number, mass or contribution to opacity in each size group are given at the foot of the table.

Because the observations cannot be taken as exact, there is a certain amount of latitude in choosing values of C_i to match the observations. Some lines of table II show alternative sets of values of C_i all leading to agreement with observation within the limits of experimental error. It will be seen that fairly big variations in distribution are possible but that the general balance between "big" and "small" drops seems fairly well fixed.

A more detailed study of how well the distributions given in table II can be expected to represent the true distributions is illustrated in fig. 1 and 2. These show, for occasions when observations were made nearly simultaneously by more than one method, distributions of several different types, all calculated to fit the optical observations and, in addition, the distributions given by cascade impactor measurements. The distributions are shown as graphs of $\log_{10} (dN/d \log_{10} D)$ vs $\log_{10} D$ (D = diameter of drop). Distributions of the type used in table II are therefore represented by a set of lines of slope -2 whose vertical positions depend on the values of C_i. In addition to the C_i

calculated for the standard groups of drops used in table II, values calculated for a different set of groups, with limits at 3.3, 6.6, 13.3 and 26.7μ are shown, to illustrate how far the distribution depends on the (arbitrary) choice of size-limits for the groups. Further distributions shown are ones calculated with a different distribution law ($dN/dr = C_i\ r^{-4}$) within each group, and one consisting not of four broad groups of drops, but of only two groups of almost uniform drops, the sizes and number of drops in the two groups being chosen to fit the observations; the fit obtained from this type of distribution is usually not as good as from the four-group type, but can be brought within the limits of experimental error in most cases.

The distributions of table IIA and fig. 1 were calculated from the angular scattering coefficients alone. They can be checked by calculating the total (i.e., "mean spherical") scattering coefficient that would be given by each distribution and comparing it with the observed attenuation coefficient for visible light. In the absence of absorption these coefficients should be equal. Exact agreement is not to be expected because the scattering measurements were made on a small sample of fog and the attenuation measurements on an extended one, but the last two columns of table IIA show that fairly good agreement is, in fact, obtained. The calculated values of total scatter for the various distributions of fig. 1 are given on the figure, and comparison with the observed attenuation shows that some distributions are in better agreement than others; the distribution with two isolated groups of drops gives particularly bad agreement. The distributions of table IIB, deduced from transmission measurements cannot, of course, be checked in this way as the attenuation coefficient for visible light was one of the quantities used in calculating distributions.

The cascade impactor results, included in fig. 1, show that some drops larger than 20μ were present, so that arbitrary cutting off of the calculated distributions at 20μ, as in table II, is unjustified. It is shown, however, that the inclusion of a group of drops of 20-40μ has no very drastic effect on the calculated distribution; the larger drops are provided, as might be expected, at the expense of the slightly smaller ones.

Fig. 1k and 2f show the best estimates of the drop size distributions in the two fogs that can be made from the present measurements. The curves have been drawn using the earlier curves as a guide, but smoothing out physically unlikely discontinuities and adjusting the final curves by trial and error until the calculated optical properties of the distributions agreed with the observations. The probable accuracy of these smoothed distributions is to be assessed by comparison with the discontinuous distributions, all of which fit the observations within the experimental accuracy. For the thicker fog, curve 1k is thought to be reasonably accurate throughout, but for the thinner fog the right-hand part of curve 2(f) is not drawn with much confidence. The group of larger drops indicated by the bump in the curve at about 10μ is so small relative to the large number of small drops that it contributes very little to the opacity or other optical properties of the fog and was revealed in the measurements only by a high intensity of scattered light at the smallest angle of observation (1°). This single observation could be explained as well by a smaller number of still larger drops as by the actual size and number shown in fig. 2. The cascade impactor result, on the other hand, suggests a group of drops at about 4μ with very few larger than 10μ.

Accepting the final curves as the best estimates of drop size distribution in their respective fogs, we can deduce the following quantities for the two fogs:

/Time and date

Time and date Visibility	2130,13.11.56 55	2320,20.12.56 330	 metres
Mass of drops	0.14	0.014	gm/m^3
Number > 7μ diam.	100	1.0	cm^{-3}
Number 1-7μ diam.	5,200	1,150	cm^{-3}
Number < 1μ diam.	> 20,000	> 10,000	cm^{-3}
Mean diameter	indefinite	indefinite	
Median diameter	indefinite	indefinite	
Mass median diam.	12	11	microns

Fig. 1 and 2 illustrate the range of variation possible in drop size distributions fitting the optical data. We can set some quantitative limits on possible distributions by considering the ratios of the contribution to attenuation at different wavelengths or to scattering at different angles made by drops of various sizes. If, for example, the attenuation is high in the 0.6 and 1.2μ bands and very low in the 10μ band, it is clear that very little attenuation is provided by drops larger than 5μ. Results can best be expressed in terms of the contribution of drops smaller or larger than certain sizes to the attenuation in the visible, the "opacity". Contributions to the total mass or number of drops are uncertain because a large mass in the form of very big drops or a large number in the form of very small drops might pass undetected by the optical methods.

For the thick fog (55 m visibility) at 1025 on 19/12/56 we find from the attenuation measurements:

drops	smaller	than	10μ	diameter	contributed	at least	60%	of	the	observed opacity
"	"	"	2.2μ	"	"	"	40%	"	"	"
"	larger	"	0.5μ	"	"	"	45%	"	"	"
"	"	"	2.2μ	"	"	"	21%	"	"	"
"	"	"	5 μ	"	"	"	19%	"	"	"
"	"	"	7μ	"	"	"	13%	"	"	"

and for the thinner fog (135 m visibility) at 1445 the same day

drops	smaller	than	8μ	diameter	contributed	at least	90%	of	the	observed opacity
"	"	"	2μ	"	"	"	75%	"	"	"
"	"	"	1.5μ	"	"	"	45%	"	"	"
"	larger	"	0.5μ	"	"	"	15%	"	"	"
"	"	"	1.5μ	"	"	"	5%	"	"	"

Similar deductions can be made from the scattering observations.

4. Discussion of results

Tables I and II contain data on most of the thick fogs at Kew in the past two winters and may be taken as reasonably representative of such fogs. They contain little information about fog or haze with visibility greater than 300 m. Cascade impactor samples were taken at all stages of fog development, but most frequently in the morning, before and during the clearance of fog. Scattered light measurements were necessarily made at night, mostly some hours after fog formed. Attenuation measurements come chiefly from the one long spell of fog (December, 1956) that has occurred since the apparatus was completed.

The most striking feature of the results is the preponderance of very small drops. The optical results, like the impactor ones, suggest that the fogs fall into two fairly distinct classes, with visibilities above and below 100 yards. In the thinner fogs practically all the drops fall into the smallest (or next-to-smallest) size-group, which contributes almost all the opacity and a large part of the liquid water content of the fog. In the thicker fogs the contribution from small drops is increased several times but

in addition there is an important component of larger drops which provides almost all the liquid water and up to half of the opacity of the fog. In most cases the division into "small" and "large" drops seems to be significant, in the sense that there is an intermediate range of size, usually around 5μ, in which drops are relatively rare. As fig. 1 and 2 suggest, the methods of observation used so far can indicate the approximate position and size of these two groups in the drop size distribution, but cannot determine the distribution of drops within each group with any precision.

It is natural to enquire how much the results reflect the situation of Kew and the influence of pollution from London. No measurements have so far been made by the optical methods except at Kew, but cascade impactor fog samples have been taken by many workers at different places, including places as remote from sources of pollution as Cornwall, Wick, Rye and the Isle of Man and in all cases (with the exception of one recently reported from Porton) the opacity deduced from the samples has been smaller by a factor of at least five (and often by a much larger factor) than the opacity deduced from visibility observations. It is thus certain that most fogs contain some components not properly sampled by the impactor as normally used; it is not possible to say, without further observations, whether the chief missing component consists of large drops lost by inertial effects or of smaller drops lost by evaporation, as at Kew.

The contribution of dry smoke particles to the Kew results has been estimated, as mentioned in section 1, from the records of the Owens automatic air filter and found to be quite small. This does not mean, of course, that the "small drops" found in Kew fogs may not consist of water condensed around particles of smoke; it does mean that the condensed water contributes much more to the opacity than the original smoke particles. No accurate measurements of humidity were made at the site of the fog measurements. The Observatory records from the North Wall screen give relative humidities of over 90% on all occasions but seldom exceeded 97% and only once reached 100%, even though many of the fogs were obviously "wet".

The simplest interpretation of the size distributions observed at Kew is that the fogs consist of a mixture of drops of the two equilibrium sizes suggested by the familiar curve of drop size against relative humidity; the "large" drops have grown so far that the effects of surface tension and dissolved substances are unimportant and their size is controlled only by the available water, with the result that they act as a regulator maintaining the humidity at almost exactly 100%; the "small" drops are the remaining nuclei grown to a size determined by this humidity and by the amount of hygroscopic matter they contain. This is a very natural picture of a fog, but its unexpected feature is the large contribution, particularly to the opacity, made by the small-drop component. The pioneer work of Wright (1939 etc.) had suggested that condensation occurred almost exclusively on large "sea salt" nuclei, that smoke particles were unaffected by condensation and that small "industrial nuclei" scarcely affected the visibility even at high humidities. More recent work by Junge (1955) and others shows that condensation is possible on a wide range of sizes of nuclei. Samples taken at humidities below about 70% show that the nuclei are usually distributed according to the law

$$\frac{dN}{d \log r} = \frac{C_1}{r^3}$$

As humidity increases the larger nuclei grow more than the smaller ones and Junge calculates that the distribution law should change to

$$\frac{dN}{d \log r} = \frac{C_2}{r^2}$$

when the air is just saturated. If supersaturation occurs the extra water will be taken up by the larger nuclei of the distribution, which will pass beyond the condensation point in their growth curve and then serve to maintain the

humidity very close to 100%. The resulting distribution would clearly be of the general form suggested by fig. 1. The actual values of C (i.e., the number of nuclei of a given size) suggested by table II are from 3 to 30 times higher than those obtained by Junge from measurements at Frankfurt; the difference can be attributed to the heavier pollution of the Kew atmosphere in foggy conditions. If the curves of fig. 1 are extrapolated down to a radius of 10^{-5} cm, we can estimate the total number of nuclei greater than this size as rather less than 10^5 per cm^3, which is of the order of magnitude suggested by Aitken counter results.

If this interpretation of the present results is correct, most of the opacity of Kew fogs is simply the result of bringing dirty air very close to saturation, and we have to enquire why thick fog is always accompanied by an appreciable concentration of "large" drops; they seem to be essential to the formation of thick fog even though they contribute only a fraction of its opacity. Two explanations seem possible. One is that the large drops play an essential role in the production of saturated air; air cooled by contact with cold ground tends to lose water faster than it loses heat and it has been suggested (Stewart, 1955) that radiative cooling not only of the air itself but also from the larger suspended particles or drops is necessary before saturation can be reached. Alternatively the large drops may appear simply because it may be inevitable that in a very nearly saturated atmosphere local fluctuations will occasionally lead to local supersaturation and the growth of some nuclei beyond their condensation point. In either case the large drops act an an indicator that saturation has been achieved.

The "thin fogs" of tables I and II contain far fewer "large" drops. In most cases there are indications (quite definite indications when a few drops are caught by the impactor or seen as specks of light in the beam of the scatter apparatus) that a few large drops are present, but in others they cannot be detected at all. The "small" drops are also less numerous (for a given size) in the thin fogs, but only by a factor comparable with the increase in visibility. The thin fogs studied at Kew have all developed from thick fogs, mostly as the fog was clearing during the morning. The development of a thick fog from a thin one has not been studied and seems to be an unusual occurrence or, if it occurs, a very rapid process. The typical sequence of events is a slow fall in visibility to values of the order of 1000 metres followed by a very rapid fall to "thick fog" conditions with visibility of perhaps 50 metres and then a long period of fairly steady conditions ending, usually after dawn, with a slow and irregular rise in visibility through "thin fog", which may persist for many hours, particularly in midwinter, to complete clearance. There is a striking difference between the rapid formation of fog and its slow clearance, in polluted regions. The fact that the "thin" clearing fogs consist almost entirely of small drops suggests that falling humidity has evaporated the big drops and that the remaining small drops are, for some reason, less sensitive to changes in humidity than in the early stages of fog formation. It may be that coagulation of nuclei or the effects of dissolved gases and chemical changes play important parts here.

The methods used so far are not very suitable for following changes in fog; even a hurried observation takes about five minutes and one with careful checks at least a quarter of an hour, while any change in scattering or attenuation properties during the observation may lead to misleading results. Nevertheless there are two periods when fairly good observations are available during clearance of fog.

Between 0830 and 1300 on 19.12.56 there was a fairly slow change from thick fog with visibility 40 metres to a thin fog with visibility about 150 metres, which persisted for the rest of the day. In the same period there was a 2°F rise in temperature (in the North Wall screen) and a fall in relative humidity from 100% to 97%. The observation at 0930 shows a more or less uniform distribution of drops, in the sense that equation (1) is followed with nearly the same value of C for all size groups; the apparent

excess of drops in the largest groups may be due to the arbitrary cutting-off of the distribution at 20μ . The next two observations show little change in the smallest groups but a marked decrease in the drops in the largest group and signs of a "gap" in the distribution between the large and small drops. The visibility increased from 45 to 60 metres, a change which is accounted for roughly by the loss of large drops. Between 1025 and 1245 there were more marked changes; the drops in the largest group disappeared altogether and relatively few remained in the 5-10μ group. The smallest group changed little but the next two groups vanished, so that by 1245 there was a typical "thin fog" with a large component of very small drops and a quite small component of larger ones. These changes were confirmed by the cascade impactor samples at 0955 and 1300; the former shows a substantial component of large drops, the latter a very small number of drops in the region of 5μ .

A somewhat similar sequence of changes occurred between 2245 on 21.12.56 and 0030 on the 22nd., when there was an increase of wind and thick fog cleared almost completely. Between 2245 and 2340 conditions were rather unsteady so that the observations may be a little unreliable, but there seems to have been a tendency for the number of drops in the large groups to increase at the expense of the smaller groups. By 0010 the wind and visibility had increased and the fog drops separated into distinct groups of large and small drops with the contribution from each group distinctly less than in the thick fog. By 0030 the fog was clearing rapidly, the contribution from the larger drops had become very small and that from the small drops had also become much smaller (in contrast to its relative constancy on 19.12.56).

5. Applications of results

Although the present results give little detail of drop size distributions, they bring out clearly the importance of the small and very small drops in determining the visibility in fog, and it is interesting to examine some of the more practical consequences of this fact.

The dominating influence of small drops suggests that in attempting to forecast visibility in fog attention should be directed towards the number, size and nature of the nuclei present in the air rather than to the amount of liquid water expected to be condensed. The fact that quite small amounts of water are needed to form a thick fog implies that the mixing of nearly saturated air at different temperatures may be more important in producing fog than is sometimes suggested. Apart from this the present results give little help with the main problem of fog forecasting, that of predicting when true saturation of the air will be attained. It is possible that the radiative and hygroscopic properties of the nuclei play an important part here, but the present techniques would require considerable modification before they could be used to study the early stages of the growth of nuclei.

In connection with the artifical dispersal of fog, the low values of liquid water content now obtained emphasize how little of the energy found necessary in the thermal method is actually used in evaporating water drops; the bulk of the energy must be devoted to lowering the humidity of the air to induce the drops to evaporate in a short enough time. The gap between the theoretical efficiency of the process and that achieved in practice thus seems even larger than had been thought and is all the more worth investigating. Similar considerations apply to the idea of drying the air by hygroscopic materials. Mechanical methods of clearing fog have hitherto been considered mostly in relation to the removal of "large" drops. If consideration is given to the "small" drops, the simple methods of dropping large drops or particles through the fog seem unpromising, because of the very low collision efficiencies expected with small drops, but the electrical and acoustic methods of inducing coagulation seem more promising because of the higher mobility of small drops. It might be well worth while to investigate the electrical state of the small drops in fogs.

/Finally,

Finally, the drop size distributions or more directly the attenuation measurements themselves, show that the use of infra-red devices should give signalling or seeing ranges appreciably greater than the "visibility", in fogs of the type found at Kew. In the thick fogs the attenuation was found to decrease fairly slowly with increasing wavelength and at 10μ was $\frac{1}{2}$ to $\frac{1}{4}$ of that in the visible region. This increased transmission might be of use in some special circumstances but bearing in mind the limitations and complexity of the available sources and detectors, it is unlikely to have any great importance. In the "thin" fogs, however, which account for a quite large proportion of all fog at Kew, transmission increases much more rapidly with wavelength and by working at about 2μ it should often be possible to get ranges five or ten times the visual range. The greatest use for such an increase of range - from one or two hundred yards to perhaps half a mile - would be in the landing and taking off of aircraft, but it seems rather doubtful if infra-red seeing devices of sufficient simplicity and reliability for general use could be developed, bearing in mind the limited number of occasions on which they could be used.

6. Future work

The two obvious limitations of the work done so far are the uncertainty and inaccuracy of the drop size distributions that are obtained and the fact that it has been done only in a rather heavily polluted atmosphere. It therefore seems desirable to develop improved methods of measurement and to use them both at Kew and at some station relatively free from pollution.

Possible developments of the optical methods are mentioned in the appendices. It is thought that it should be relatively simple to develop either of them to give approximate drop-size distributions, analysed into five or six size groups, with a good deal less uncertainty than the distributions obtained from the present apparatus. The precision of the results, however, depends a good deal on the type of fog studied; a fog with very uniform drops will give simple and unambiguous results but there will always be some doubt as to the exact form of a broad distribution. The most effective size ranges of the two methods are not the same. The scatter method could be made to give accurate information about the largest drops of a distribution, but cannot easily discriminate between different sizes among the smaller drops. The attenuation method is more satisfactory for small drops but has poor discrimination for large ones, at any rate if measurements are confined to wavelengths below about 13μ, as is almost inevitable. It therefore seems necessary to continue to use both methods together if complete results are to be obtained.

The cascade impactor is a very convenient instrument to use and gives direct and detailed results, though the counting of drops is laborious. In its present form it certainly gives inaccurate results. Proposals have been made (May, private communication) that would probably make it an effective sampler down to at least 5μ, but at the cost of a considerable increase in complexity. It seems unlikely that any device of this type would be satisfactory as a sampler of the smallest drops.

It is suggested that the most economical line of development would be to improve the scatter method in the direction of increased accuracy, range of angles, sensitivity, ease of operation and portability and to use it at various places. The attenuation method should be retained and improved at Kew and the cascade impactor, in its simple form but with any precautions that can be suggested to avoid error, should be used as a general check on the size distribution of the large drops.

This programme should give results of the type of table II but with less uncertainty and greater precision, and for fog in clean as well as dirty air.

If still greater precision in drop size distributions is required considerable development of the optical techniques (and of the associated calculations) would be necessary and it would be desirable to examine other

possible techniques such as photography for the larger drops and electrostatic or spider-web capture for the smaller ones. For most purposes, however, relatively crude approximations to the drop size distribution seem sufficient and any further extension of the present work could probably be made more profitably in the direction of exploring the connection between the fog drops and the nuclei present before fog forms. There are obviously many other interesting lines of enquiry such as the electrical state of the drops, their interaction with polluting gases, their distribution with height and possible collisions between drops of different sizes, but present resources are likely to be fully occupied with the development and use of the scatter and attenuation methods as outlined above.

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Appendix I

Measurements with a Cascade Impactor

1. Sampling technique

The instrument has been fully described by May (1945), with details of the method of taking and examining samples. In the present work the only major departure from the methods described by May was the use of the Naphthol Green-in-gelatine coating on the slides (Liddell and Wootten, 1957), but the following minor points may be worth noting. Aspiration was provided not by an air pump but by a simple water aspirator fitted with a large-bore quick-acting tap. The head of water was adjusted so that the rate of aspiration was close to the value of 17.5 l/min recommended by May. In use, the water run out of the aspirator was collected and measured as a convenient way of finding the volume of air sampled, without the need to measure short intervals of time. In most fogs samples of a few hundred cm^3, taken in times of one or two seconds, gave drop deposits of convenient density. Most of the samples were taken in very light winds (1-2 ft/sec) and at first they were taken with the bell-mouth adaptor fitted to the impactor and with the intake aperture facing vertically upwards. This method often produced a rather irregular-shaped deposit on the first slide, and later samples were taken with the aperture facing into what wind there was and inclined slightly upwards; this produced much more even deposits of drops.

2. Examination of samples

The slides were examined under a good-quality microscope with objectives of 16, 8 and 4 mm. The drop stains were sized with the help of an eyepiece graticule calibrated against a 1/100 mm scale. The stains on the first and second slide were normally easy to see and there was little difficulty in sizing and counting them, provided the slides were not overexposed. Several "traverses" across the deposit on the slide were usually made, to obtain a good estimate of the numbers of drops. On the second slide there was usually a considerably higher concentration of drops at the ends than in the middle of the trace of drops. Although this limits the accuracy of estimates from the slides, the limitation is not important in the present work.

3. The third slide usually had a fairly even deposit, slightly denser towards the end of the trace, but the distinctness of the stains was rather variable. On some slides they were quite plain but on others they were barely visible and very hard to size and count. Presumably some slides were better prepared than others, though no conscious changes in technique were made. The third slide often had a fairly sparse deposit of opaque particles of irregular shape in addition to (and apparently not connected with) the drop stains. On the fourth slide these particles were smaller and much more numerous. On none of the fourth slides was it possible to identify drop stains with any certainty. On some there were quite small numbers of ring shaped stains that may have been due to water drops, but it was impossible to be sure that they were genuine stains and not out-of-focus images of opaque particles or diffraction rings surrounding them. It is felt that if stains equivalent to those made by the smaller drops (1 μ diam.) on the third slides had been present on the fourth slides, they could have been identified fairly confidently.

4. Tests in artificial fog

When it was realized that the impactor samples were quite incapable of accounting for the observed opacities of Kew fogs, experiments to check the operation of the impactor were started. These were done in a small (8 $ft.^3$) heat-insulated, waterproofed room, the "fog chamber", in which artificial fogs could be produced and maintained. The opacity of the fogs was measured by measuring the attenuation of a beam of light in the chamber with a simple photoelectric meter; with a small chamber it was difficult to measure attenuation coefficients of less than about 100 km^{-1} with much accuracy. Most of the results to be quoted are therefore only semi-quantitative.

5. The first method of making artificial fogs at Kew was by using an ordinary paint spray, with air pressures of 20-50 lb/sq.in. Samples of fogs made in this way were very similar to natural fog samples. Drops were caught on the first three slides, but their total area was far too small to explain the observed attenuation coefficient. It was suspected that very small drops were responsible for the extra attenuation.

6. Apparatus was made for measuring the light scattered at small angles (1° - 5°) by fog. From these measurements it was possible to deduce, within fairly wide limits, the size distribution of the drops responsible for the attenuation. It was found that most of the attenuation in the spray fog was, in fact, due to small drops, though the predominant size was 1-3μ rather than below 1μ, as had been guessed.

7. Changes in spraying technique were tried in an attempt to produce fogs not containing small drops, the size being checked by the light scatter method. It was found that by using air pressures below 10 lb/sq. in. and a low rate of water flow the desired type of fog could be made. Samples of these fogs gave drops mostly in the range 15-30μ and the attenuations deduced from the drop samples agreed well with those observed directly - the first time such agreement had been obtained.

8. Attempts were next made to produce fogs with drops predominantly in the range 5-10μ, which should be caught on the second slide. Spray methods were unsuccessful but steam fogs produced by boiling water inside the fog chamber were found to have a very suitable drop size distribution, sharply peaked at about 7μ. Most samples from these fogs contained enough drops to account for the observed attenuation (if the fog was at all dense the second slide was flooded) but a few contained far too few drops, perhaps because the fog was not uniform. All slides were found to have a "crazy paving" pattern on the green gelatine and the drop stains were often hard to see. Some stains were in focus at the same level as the crazy paving pattern but others seemed to be at a lower level and were diffuse and partly obscured by the out-of-focus crazy paving. The effect was attributed to the high humidity of the warm fog relative to the impactor and, in order to avoid it, the impactor (with its slides inside) was warmed over an electric stove before being taken into the fog. This procedure entirely eliminated the crazy paving effect and gave very well defined drop stains, but it also resulted in much less dense samples so that the attenuation deduced from the samples was much less than that observed directly. It seems clear that with a warm impactor the drops evaporate to a considerable extent, in the space outside and above the impactor, during their passage through it or after impinging on the slide. The amount of warming required to produce the effect is not large, though it has not yet been investigated thoroughly. The impactor was usually heated about 20°C above room temperature, then taken into the fog where it was kept for about 10 minutes before sampling. The temperature difference between impactor and its surroundings was found to fall by half in about 6 minutes. At the time of sampling the impactor was probably about 5°C warmer than the fog.

9. In the light of these experiments, further samples of small-drop spray fogs were taken, first with the impactor at about fog temperature, then with the fog chamber warmed, so that the impactor was cooler than the fog. With equal temperatures, drops were found on the second and third slides, but in far too small numbers to explain the observed attenuation. No drops were found on the fourth slide, but there was a fairly dense deposit of opaque particles. With the fog warmer than the impactor the second and third slides were not much changed (though showing "crazy paving") but the trace on the fourth slide was "flooded", the dye being almost completely washed away from a rather well-defined area about equal to that of the jet. The light-scatter observations in these fogs indicated that they were composed mainly of drops below 5μ, with (less certainly) a predominant size of 2-3μ.

/10.

10. Another way of avoiding evaporation is by using fogs of salt solution rather than of water. Somewhat different spray arrangements were used and the light-scatter measurements suggested that most drops were between 2 and 10μ, with few larger or smaller ones. A sample in a moderately dense fog gave flooding on second, third and fourth slides (in conditions where a water fog would have given only thinly covered slides) and a sample in a thin fog gave about half the number of drops required to explain the attenuation. The drop stains were not well defined and usually irregular in outline, suggesting that the salt interacted with the dye. These experiments, though not at all precise, suggest that if evaporation is avoided the impactor gives a much more nearly true sample.

11. The general result of the various tests is thus that the impactor gives a roughly correct sample if it is a few degrees cooler than the fog and a decidely incorrect one if it is a few degrees warmer. If it is at nearly the same temperature as the fog (i.e., prepared in a room at the same temperature, then left in the fog for some time) drops large enough to appear on the first slide are sampled correctly, those appearing on the second slide are probably somewhat underestimated and those on the third and fourth slides are very seriously underestimated. Whether a true sample could be obtained by very accurate control of the temperature (either to the fog temperature or to one a degree or two lower) is not known, but it is quite clear that for ordinary fog samples serious underestimation of the smaller drops would be expected.

12. The explanation of these results is not obvious. If air passing through the impactors undergoes "adiabatic" expansion it will be cooled and its relative humidity raised. If it undergoes "throttled" expansion it will be cooled to a much smaller extent and the effect of the expansion will be to lower the relative humidity (by nearly 4% at the fourth jet). The actual flow process is complicated and probably does not fit any simple model, so that it is almost impossible to say what the actual changes of relative humidity are. In any case, however, it is hard to see how they could exceed about 5%, and changes of this amount would not be expected to cause appreciable growth or shrinkage of fog drops in the very short time of their passage through the impactor. On the other hand, there is the observed fact that changes of humidity of about this size brought about by warming the impactor do actually result in loss of drops. It may be that evaporation can go on after the drops have reached the slides.

13. The results obtained in natural fogs were reviewed in the light of the artificial fog experiments. The first point noticed was that none of the slides showed the "crazy paving" effect that is characteristic of an impactor below fog temperature. The second point concerns the relative numbers of drops of different sizes appearing on the different slides of a sample. We define the "halfway size" for two successive slides as the size that appears with equal frequency on the two slides. According to Casella's curves the halfway size is about 12μ for slides 1 and 2, 4μ for slides 2 and 3, and 1.5μ for slides 3 and 4. (Sampling unit density drops at 17½ l/min.) The halfway sizes actually found in the natural fog samples are about 10μ for slides 1 and 2, 2.5μ for slides 2 and 3 and less than 1μ for slides 3 and 4. The fact that these halfway sizes are smaller than those found in tests with non-volatile drops (i.e., Casella's curves) and that the difference is, in proportion, greatest for the smallest drops suggests strongly that drops are being lost in each stage of the impactor, as would happen if evaporation were occurring. The suggestion is supported by details of the drop size distributions; there is a fairly consistent tendency for minima to occur in each of the size ranges for which drops are shared between two slides. This can hardly be a regular natural phenomenon and is much more likely to be due to losses in the impactor. The effect could, however, be produced by relatively small systematic errors in the microscopic sizing of drops and could, by itself, only provide clear evidence for or against the evaporation hypothesis after careful statistical examination.

/14.

14. The possibility that drops might be lost by deposition on the walls of the impactor was investigated by May, but a few additional tests with water fog were made in the Kew chamber by inserting very small pieces of dye-coated cover glass in various positions in the impactor. The results confirmed that wall losses were negligible.

15. Losses of large drops

The artificial fog experiments show that the impactor samples "large-drop" fogs correctly within a factor of about two, but are not accurate enough to detect smaller errors and have not been extended to drops larger than about 30 μ. Experiments by May (1956) have shown that errors of up to 50% may arise when sampling large drops in light winds because drops larger than 20 μ may not follow the air streamlines closely enough to enter the impactor. Another type of error seems likely with the very small air samples found necessary in fog work; it can be calculated that if 500 cc of air are drawn into the impactor, starting with the air at rest, some 30% of 30 μ drops and 70% of 50 μ drops will fail to reach the first slide of the impactor, being left behind as the air accelerates. These inertial errors have not been studied experimentally at Kew.

16. Size of sample; overlapping of stains

Although the samples taken in natural fogs do not contain nearly enough drops to account for the observed opacity, the number of drops in many samples from thick fogs was large enough to cause a serious overexposure of the slides, even though the volume of air sampled was kept as small as possible. This implies that if the impactor sampled all the drops correctly, the problem of obtaining satisfactory exposures would become very serious. Experience shows that the best slides are those where the drop stains cover about 1/50 of the area of the "exposed" part of the slide; if the coverage is greater than about 1/20, counting and sizing becomes very difficult because of overlapping of the stains. The area of the stains is proportional to the cross-sectional area of the drops and hence, approximately, to the product of the attenuation coefficient and the volume of fog sampled. We find, for the area, A, of the stains from the drops in C cm^3 of fog with attenuation coefficient σ,

$$A = 3.1\, C\, \sigma$$

or

$$A = \frac{12.5\, C}{V}$$

where σ has been taken as 4/V, V being the visibility in the fog. The fractional coverage of the slides is therefore

$$\frac{A}{S} = \frac{12.5\, C}{VS}$$

where S is the area of the slides exposed in the impactor. If A/S is to have the desired value 1/50 we find that the volume of fog that should be sampled is given by

$$C = \frac{1}{50}\,\frac{V.S}{12.5}$$

The total area of slides exposed in the impactor is about 2.5 cm^2, so that

$$C = \frac{V}{250}\ \text{cm}^3 \quad (V \text{ in cm})$$

or

$$C = 50\ \text{cm}^3 \text{ if } V = 125\ \text{m}.$$

If therefore, the impactor was to sample correctly all the drops which affect the visibility in a fog with visibility 125 m, it would be necessary to restrict the volume of air sampled to 50 cm^3. The impactor itself has a volume of at least 100 cm^3, so that it seems quite impracticable to take such a small sample. The situation is even worse if the smaller drops contribute most of the opacity of fog because then the sample is concentrated on the very small exposed area of the later slides (less than 0.5 cm^2 for the third and fourth slides together).

17. Possible modifications to impactor technique

Proposals for overcoming the limitations of the cascade impactor as a fog sampling device have been made by May (private communication.) He suggests that loss of large drops could be avoided by mounting the impactor inside a wind tunnel, through which fog would be drawn at the optimum sampling speed for the impactor (~ 8 m.p.h.); that the problem of overexposure of the slides could be met by moving the slides past the sampling slits of the impactor and thus spreading the deposit over a greater area; and that evaporative losses could be avoided by using only the first and third stages of the impactor (May believes that little evaporation can occur before the second slide, in normal use) and applying corrections to the number of small drops recorded, to allow for those that would slip past the third stage. The drawback to these proposals is that they would convert the impactor from a simple and handy device into a quite large and complicated installation. Also, while they seem likely to overcome the errors for large drops and so should lead to quite good estimates of the distribution of the bulk of the water in fogs, it seems far from certain that they would really be effective in avoiding or allowing for losses of small drops, so that the opacity - producing components of fogs might still not be measured adequately.

Appendix II

Scattered light measurements

1. The apparatus is shown schematically in fig. 3 (not to scale). The slits S_1 and S_2 select a narrow beam of light from the 12 volt 48 watt filament lamp C. The lenses L_1 and L_2 help to illuminate S_1 evenly and the various auxiliary screens reduce stray light. These components were all mounted on a single 10 ft beam which could be set up on a light framework indoors or out. Light scattered from a portion of the beam at O was measured by a photometer P which pivoted about O to receive light scattered at different angles. The photometer P was a Salford Electrical Instruments photographic exposure photometer modified by substituting a 10 cm focus objective lens for its own short-focus one so that brightness could be measured for a field of only about 1/10 degree rather than for the 1 degree field of the original instrument. The photometer contains a Lummer-Brodhun head with a small oval comparison spot illuminated through variable filters by a small electric bulb standardized against a photocell. Auxiliary filters are provided for covering a wide range of brightness and for colour correction. The aperture of the objective lens was restricted to a slit 0.9 cm x 2.0 cm by a screen fixed just outside the lens. The screen extended for about 15 cm on each side of the lens and was marked with a scale in centimetres, so that the angular position of the photometer with respect to the light beam could be found by observing the position of the beam on the scale. The photometer head and its objective lens were adjusted so that parallel light from the direction of the pivot O was brought to a focus on the comparison spot of the photometer cube. The photometer was carried in a light but rigid metal frame; the end nearest the observer rested on a small table and could be slid from side to side by the observer, while the other end consisted of a metal beam extending to the pivot O which was carried on a theodolite tripod. The fog under observation at O was therefore relatively free from interference; it was about 3 metres from the light source C, about 1 metre from the final slit S_2 and its supporting frame, and about 1 metre from the photometer head and the observer. In the immediate neighbourhood of O the only interference was from the tripod and the beam of the photometer resting on its pivot; these were several centimetres below the point from which the light was scattered.

2. Measurements were made by turning the photometer to each of the desired angles of observation in turn and adjusting the brightness of the comparison spot until it matched the surrounding field provided by light scattered from the fog. The photometer scale was marked in logarithmic units of brightness and it was found that settings could usually be repeated to within 0.1 $\log_{10}$ units, though in some cases the fog was patchy and less accurate readings were obtained. The matching was done with white light, using the "artificial light" colour correction filter in the photometer. There was often a tendency for the scattered light to appear rather too blue at small angles and rather too red at large angles, but not sufficiently to cause serious errors in matching (the readings were scarcely affected if the "daylight" filter was used rather than the "artificial light" one). Readings were normally taken to one side of the incident beam only, but checks on a number of occasions showed that readings on the other side were very nearly the same.

3. At the end of each series of scattered light readings a piece of white card was placed at the pivot O, normal to the incident beam, and the photometer was swung right round to view the patch of light from a direction close to that of the beam. Brightness readings were taken, just as for the scattered light, to provide a measure of the flux in the beam. The reflectivity of the card (ρ) was later measured by comparison with a magnesium oxide surface.

4. The relative values of the scattering coefficient of the fog at different angles (b_θ) were taken as proportional to the brightness readings on the photometer scale, B_θ , multiplied by the sine of the scattering angle θ , because the depth of the illuminated fog seen through the photometer was inversely proportional to the sine of the angle of observation. The absolute values were calculated from the formula

$$b_\theta = \frac{B_\theta}{B_0} \frac{\rho}{\pi a}$$

/where

where B_o is the brightness reading obtained with the beam of light incident on the white card and a is the width of the aperture in front of the photometer lens. (It is necessary to use this width in the calculations rather than the actual width of the beam of light at O to allow for the fact that the measurement of B_o is made on a patch smaller than the photometer aperture and with a photometer focussed for infinity).

5. The accuracy of the measurements was limited primarily by the accuracy of the photometer wedge, by the difficulty of matching the comparison spot in view of its small size and low brightness and by the variability of the fog from moment to moment. Errors due to secondary scattering of light, to misplacement of the pivot O or to bad alignment or focussing of the photometer were small by comparison. One correction which had to be applied was for incorrect density of one of the range-changing filters of the photometer, which was found to have a density of about 2.2 instead of the nominal 2.0 ($\log_{10}$ units); the calibration of the main wedge filter of the photometer was checked roughly by an inverse square law method and found to be correct within about 0.1 $\log_{10}$ units. Quite erroneous results were obtained in the early stages through condensation of water on the photometer lenses. This was avoided by keeping the photometer in a heated hut except for fairly brief periods of observation. The onset of condensation is easy to detect.

6. The main defects of the method just described are that it depends on visual photometry, which is slow and not very accurate in the circumstances, and that it uses white light. It is planned to construct a more accurate and convenient apparatus, sketched in fig. 4.

A narrow beam of monochromatic light is provided by the high pressure mercury lamp S, filter F and circular aperture A. The main beam is absorbed in the light trap T but scattered light is collected by the lenses L_1 and L_2, and the aperture B allows light from a small section of the beam to pass on the photomultiplier P. This light is further restricted, by the movable annular aperture C, to that which has been scattered within a narrow range of angles; the mean angle of scattering can be varied by sliding C along the axis of the system. It is not certain that this system of apertures will eliminate unwanted light sufficiently. It may be necessary to employ pairs of annular slots close to each lens to define the length of beam and range of angles more closely.

Appendix III

Attenuation measurements

1. The experimental arrangement is sketched in fig. 5. Four sources of radiation were provided, mounted in line about 3 ft apart on a light framework 4 ft above the ground. The sources were

W. A 100 watt electric lamp run at full voltage

X. A 2000 watt electric lamp run at a much reduced voltage giving a temperature of about 1200°C

Y. An electric hotplate of 20 cm diameter with a well oxidised surface, run at a very dull red heat

Z. A similar hotplate painted with optical black and run at a surface temperature of about 100°C.

The radiation from these sources was received through the open window of a hut 46 m distant, with the arrangement shown. The front silvered spherical mirror M, of aperture about 20 cm and focal length 60 cm, reflected radiation through the apertures and on to the thermopile of a Linke-Feussner radiometer, I. The mirror was tilted slightly from a vertical plane and the radiometer mounted below its axis, so that a horizontal beam of radiation falling on the mirror was not obstructed by the radiometer. M and L were mounted on a framework with one end pivoted, so that it could turn about a vertical axis, and the other end free to slide on a rigid table. The receiver assembly could thus be turned to accept radiation from each source in turn. The mirror M was just large enough to fill the field of view of the radiometer. The thermopile had a diameter of 1 cm so that the cone of radiation accepted by the receiver had a half-angle of just under 0.5 degrees. An experimental test of the angular response curve of the receiver showed that it was reasonably flat-topped and that the response fell to half its full value at about 0.3° off the axis. The radiometer was connected to a sensitive moving-coil galvanometer whose voltage sensitivity (with radiometer in circuit) was checked from time to time by an auxiliary circuit and found to vary by less than 3 per cent.

2. Measurements were made on the four sources with the following filters in position in the radiometer:-

W. RG2 filter 1.55 mm thick, passing radiation between about 0.63 and 2.8 μ

X. The same

Y_1. The same

Y_2. Quartz filter 1.60 mm thick passing radiation up to about 4 μ

Z. No filter.

It was assumed that the sources radiated as black bodies at temperatures of 2750, 1500, 850 and 375°K respectively, and from the theoretical variation of radiated energy with wavelength, the filter characteristics tabulated by Linke (1933) and, for the longer wavelengths, the approximate atmospheric absorption spectrum, the curves shown in fig. 6 were calculated, giving the effective distribution of energy in wavelength for the bands in which measurements were made. The short-wave measurements V, were made on source W with a "photoelectric visibility meter, Mk.II", as receiver, placed alongside the radiometer receiver. The energy curve for V is determined by the radiation curve of the source and the response curve of the selenium cell in the receiver.

/3.

3. Measurements were made by fitting the appropriate filter, turning the receiver to view the space between two sources or beyond the line of sources, reading the galvanometer, turning the receiver to view the desired source and again reading the galvonometer. The readings were normally repeated several times in an attempt to eliminate drifts, which were always troublesome, and to reduce the effects of random variations. Measurements were made daily in clear weather (visibility greater than 1 Km) for about three months and as often as possible in fog. The clear weather measurements were taken to represent 100 percent transmission in the wavebands concerned, and the attenuation due to fog was calculated by expressing the signal received in fog as a fraction of that received in clear conditions. The clear air measurements had standard deviations of about 10% for sources X and Z, 13% for Y and 20% for W. These variations probably come from several causes; the source temperatures were not controlled and may have varied because of mains voltage variations and the effects of wind and air temperature; background radiation received in the zero positions between the sources may have varied; mechanical imperfections in the receiver probably led to errors in alignment on the sources. The large deviations for source W may have been due to variations in contact resistance of the lamp holder, as most of the variance came from a fairly small number of highly irregular readings. In the conditions of fog measurements most of these errors were probably smaller and it is thought that the 100 percent transmissions values, taken from clear air observations just before and after the fog rather than from the mean of the whole set of clear air observations, were accurate to rather better than 10 percent for all wavebands. The fog measurements themselves were presumably subject to a similar error. The combined effect of these errors of observation of the attenuation coefficients given in table II varies with the amount of the attenuation; for very low attenuations ($< 10\ Km^{-1}$) the standard error of the values in the table is about $2\ Km^{-1}$, at $20\ Km^{-1}$ it is about $3\ Km^{-1}$ and for the highest values (about $100\ Km^{-1}$) it is about $6\ Km^{-1}$.

4. The effects of water vapour absorption (as distinct from scattering and absorption by water drops) were studied by examining the clear air observations in relation to vapour pressure. Dividing the observations into two groups, with high and low values of vapour pressure (means of 9.7 and 6.9 mb respectively), no significant difference in the radiation received from source Z (which should be most affected by water vapour absorption) could be detected. It was concluded that the values of table II represent the effects of suspended drops or particles and are only negligibly affected by water vapour.

5. It has been pointed out by Middleton (1952) that all transmission measurements of this type may underestimate the attenuation coefficient because a certain amount of scattered light will enter the receiver in addition to the unscattered direct beam which is supposed to be measured. The error is small provided the cone of radiation accepted by the receiver is small and provided the attenuation being measured is not too large. Rough estimates suggest it is negligible in the present work except in the thickest fogs, where it might lead to slight underestimation of the attenuation coefficient at the shorter wavelengths. The measurements at the shortest wavelength of all, however, (waveband V) would be less affected than the others because the photoelectric receiver had a rather narrower field of view than the radiometer.

6. The main defects of the present method of measurement are the great width and poor definition of the wavebands used and the general low accuracy of measurement, chiefly attributable to the variability of the sources used and the impossibility of checking their outputs during fog. It will clearly not be possible to overcome these defects without using considerably more elaborate apparatus. For the isolation of reasonably narrow wavebands (a bandwidth of about $0.1\ \lambda$ at wavelength λ would be suitable) it will be necessary to use a simple form of infra-red spectrometer, at any rate for the longer wavelengths; for wavelengths below about $2\ \mu$ it might be preferable to use filters. To achieve satisfactory accuracy, it will be necessary to arrange the optics of the measurement so that transmission over long and short paths can be compared and variations in source and receiver allowed for.

Table I. Data from cascade impactor (C) and sedimentation (S) samples (all in Km^{-1})

Date	Time G.M.T.	Visibility metres	Type of sample C or S	Cross-sections of drops in diameter ranges						$\sigma_d = \frac{1}{2}\sum_i S_i$	$\sigma = 3.91/V$	σ_s
				0-1.25μ	1.25-2.5μ	2-3-5μ	5-10μ	10-20μ	> 20μ			
				S_1	S_2	S_3	S_4	S_5	S_6			
1955												
30. 8	11.00	360	C	0	0	0	0.01	0.01	0	0.04	11	1.0
24. 9	09.30	220	C	-	-	0.03	0.1	0.2	0.05	0.76	18	4.5
11.10	09.20	75	C	0.02	0.03	0.4	0.5	0.9	1.2	5.4	55	1.0
11.10	18.15	20	C	0.001	0.003	0.8	3.8	3.9	0	17.0	200	1.0
12.10	10.20	360	C	0	0	0.1	0.04	0.03	0.04	0.4	11	1.0
1.11	10.00	135	C	0	0	0	0	0	0	0	30	4.5
1.11	10.30	200	C	0	0	0	0	0	0	0	20	4.5
30.11	09.15	55	C	0.03	0.19	0.53	1.1	3.2	2.7	15.4	75	3.0
30.11	09.15	55	S	-	-	-	0.7	2.1	2.0	9.6	75	3.0
30.11	10.45	75	C	0.03	0.21	0.29	0.21	0.50	0.27	3.0	55	3.0
30.11	10.45	75	S	-	-	-	0	0.6	0.4	2.0	55	3.0
30.11	12.00	220	S	-	-	-	0	0	0	0	18	4.5
30.11	21.15	220	C	0	0	0	0	0	0	0	18	4.5
1.12	18.00	45	C	0.005	0.07	0.6	2.9	2.2	0	11.6	90	4.0
1.12	21.40	90	C	0.03	0.07	0.04	0.002	0	0	0.3	45	4.0
1.12	23.00	90	C	0.03	0.1	0.05	0	0	0	0.3	45	6.2
2.12	09.20	45	C	0.02	0.2	0.9	1.6	2.4	2.9	16.0	90	3.0
2.12	10.10	45	C	0.02	0.2	1.0	1.5	2.5	2.5	15.4	90	4.0
2.12	10.45	360	C	0	0	0	0	0	0	0	11	4.5
17.12	09.45	40	C	0.03	0.12	0.5	1.4	4.3	2.5	17.6	100	2.0
17.12	10.00	40	S	-	-	-	1.8	5.0	2.8	19.2	100	2.0
17.12	11.00	90	C	0.01	0.12	0.3	0.5	1.0	0.5	4.6	45	3.0
17.12	11.20	100	S	-	-	-	0.34	0.65	0.72	3.5	40	3.0
19.12	10.45	90	C	0.01	0.09	0.19	0.12	0	0	0.8	45	-
19.12	12.10	200	C	0	0	0	0	0	0	0	20	-
1956												
4. 1	11.55	20	C	0.07	0.23	1.05	0.36	0.15	0	3.7	200	7.5
5. 1	12.40	60	C	0.15	0.29	0.66	0.07	0	0	0	65	4.5
5. 1	15.30	16	C	0.17	0.34	1.5	1.0	0.75	0.3	7.1	250	7.5
5. 1	16.30	15	C	0.18	0.86	0.50	0.2	0.9	0.4	6.0	270	10.0
5. 1	17.00	18	S	-	-	-	1.6	0.8	0.33	5.5	225	10.0
12.10	01.25	33	C	0.01	-	-	2	5.0	0.3	15	120	3.0
12.10	01.33	33	S	-	-	-	1.1	9.0	1.1	22.4	120	3.0
16.10	00.15	30	C	-	-	-	2.0	9.9	2.7	29	135	2.0
16.10	00.15	30	S	-	-	-	12.5	13.6	1.2	54.6	135	2.0
13.11	21.50	50	C	0.07	0.32	0.25	0.53	2.6	2.6	12.8	80	4.0
10.12	09.55	45	C	0.01	0.09	0.4	1.3	1.7	0.6	8.2	90	2.0
10.12	10.25	55	S	-	-	-	0.3	0.4	0.2	1.8	75	3.0
18.12	13.00	135	C	0.02	0.03	0.06	0.09	0	0	0.4	30	6.0
18.12	15.25	135	S	-	-	-	0	0	0	0	30	6.0
20.12	12.15	220	C	0.02	0.05	0.05	0.1	0	0	0.4	18	3.0
20.12	16.20	180	S	-	-	-	0	0	0	0	22	3.0
20.12	23.25	330	C	0	0	0.01	0.02	0	0	0.06	12	1.5
21.12	23.45	75	C	0.07	0.15	0.4	0.8	1.5	0.8	7.4	55	1.0
21.12	23.45	75	S	-	-	-	0.6	2.9	2.1	11.2	55	1.0
22.12	00.20	330	C	0	0.01	0.05	0.3	0.7	0	2.2	12	1.0

Table IIA. Results of optical measurements: scattered light measurements

Date	Time	Visibility	Observed scattering coefficients (Km^{-1})				Values of C_i (Km^{-1}) for drop size distributions which fit the observations: Range of drop diameters				Calculated total scatter coefficient	Observed attenuation coefficient
	G.M.T.	metres	1^o	2^o	3^o	5^o	0-2½ μ	2½-5 μ	5-10 μ	10-20 μ		
1956							$C_{1,2}$	C_3	C_4	C_5	Km^{-1}	Km^{-1}
12.10	00.25	33	8900	2250	760	450	13	0	9.0	18.5	159	120
12.10	00.35	33	6300	1120	480	350	12	0	0	21	137	120
14.10	00.25	20	5100	1600	610	320	10	0	9.3	12	122	195
14.10	01.50	33	4700	1130	610	250	0	13	1.8	13	62	120
							2.2	9.0	7.3	11	77	
15.10	22.45	20	14900	2850	860	400	12	0	7.3	48	205	195
							9.3	1.9	9.3	45	191	
16.10	00.15	30	10400	2230	560	230	16	0	14	29	215	130
13.11	21.30	55	3500	1000	540	260	5.1	5.1	5.1	8.3	80	71
19.12	17.40	200	172	102	84	86	3.2	0	0	0.3	26	19
							3.2	0	0.06	0.19	25	
19.12	18.45	300	66	47	38	50	1.7	0	0	0.05	13	13
20.12	17.45	160	101	80	80	50	1.2	1.2	0	0	12	24
							1.4	0.9	0.06	0		
20.12	23.15	330	75	45	38	43	1.5	0	0	0.09	12	12
21.12	22.45	70	2340	1170	700	465	12	8.0	2.9	0.4	119	56
21.12	23.05	80	1780	1000	680	400	5.9	14	0	2.9	86	49
21.12	23.35	75	2860	1440	770	320	5.9	8.6	9.9	3.2	95	52
21.12	23.40	75	4040	1810	970	570	21	0	12	5.9	200	52
22.12	00.30	350	357	143	108	114	4.2	0	0	0.7	34	11
1957												
2. 1	05.20	45	3870	1440	615	322	9.3	3.2	11	6.7	117	87
2. 1	06.55	110	100	80	85	80	3.0	0	0	0	23	36
2. 1	07.05	80	324	178	131	126	3.8	1.6	0	0.4	34	49
To obtain number/cm^3 of drops in each size group, multiply values of C_i (in Km^{-1}) by the factors:-							(×)	104	26.1	6.5		
To obtain liquid water content (mgm/m^3) due to drops in each size group, multiply values of C_i (in Km^{-1}) by the factors:-							2.28	2.28	4.55	9.11		
To obtain opacity (in Km^{-1}) due to drops in each size group, multiply values of C_i (in Km^{-1}) by the factors:-							7.75	2.40	2.12	2.09		

Table IIB. Results of optical measurements; measurements of transmission of radiation

Date	Time	Visibility	Observed attenuation coefficients (Km^{-1}) in wavebands centred on:					Values of C_1 (Km^{-1}) for drop size distributions which fit the observations:- Range of drop diameters				
	G.M.T.	metres	0.6 μ	1.2 μ	2.3 μ	3.4 μ	10 μ	0-1.25 μ	1.25-2.5 μ	2.5-5 μ	5-10 μ	10-20 μ
								C_1	C_2	C_3	C_4	C_5
1956												
13.11	20.00	15	260	-	-	-	75					
13.11	22.10	45	90	-	-	-	33					
19.12	08.30	35	100	75	67	-	-					
	09.30	45	88	75	67	60	37	7.0	1.6	9.5	1.6	16
								6.4	6.4	3.2	6.4	16
	09.45	45	88	60	-	53	34					
	10.25	55	74	58	40	46	21	6.4	8.0	0	9.5	4.8
	11.10	60	64	43	35	27	15	8.6	3.2	3.8	3.2	6.4
	12.45	135	30	9	7	4	0	6.4	0	1.6	0	0
	14.45	130	32	11	4	7	0	8.0	0	0	1.4	0
	16.10	110	37	9	3	6	0	8.0	0	0	1.4	0
	18.15	180	22	5	0	0	0	5.4	0	0	0	0
20.12	11.30	150	28	10	2	-	0)					
	14.30	160	25	9	2	6	0)	6.0	0	0	1.3	0
	16.40	170	23	10	4	6	0)					
	22.30	290	14	6	0	-	0	2.5	1.6	0	0	0
	23.30	320	12	5	0	1	0	2.4	1.1	0	0	0
21.12	23.00	80	49	46	24	36	10	4.8	8.0	0	8.0	0
	23.25	65	64	46	47	44	28	8.0	0	3.2	6.4	9.5
22.12	00.10	175	23	17	12	14	6	1.6	3.2	0	2.5	1.6
1957												
2. 1	06.15	200*	70	23	-	64	14	Observations cannot be fitte				
	06.40	225*	31	11	14	6	2	4.8	0	3.2	0	0
	07.35	225*	48	31	17	14	4	6.4	7.7	0	1.9	1.0
To obtain number/cm^3 of drops in each size group multiply values of C_1 (in Km^{-1}) by the factors:-								(∞)	416	104	26.1	6.5
To obtain liquid water content (mgm/m^3) due to drops in each size group, multiply values of C_1 (in Km^{-1}) by the factors:-								1.14	1.14	2.28	4.55	9.11
To obtain opacity (in Km^{-1}) due to drops in each size group, multiply values of C_1 (in Km^{-1}) by the factors:-								4.7	3.0	2.40	2.12	2.09

* These figures give the general visibility. The transmission measurements were made in a denser layer of ground fog within the Observatory enclosure.

Table III

A. Contributions which groups of drops with $C_i = 1\ Km^{-1}$ make to scattering coefficients at four angles of observation for light of wavelength 0.525 μ.

Km^{-1}		Size ranges: diameters in microns			
		0 - 2.5	2.5 - 5	5 - 10	10 - 20
Angle of scattering	1°	31	49	132	294
	2°	30	42	77	35
	3°	28	33	30	7
	5°	25	17	2	2

B. Contributions which groups of drops with $C_i = 1\ Km^{-1}$ make to attenuation coefficients in five waveboands (see fig. 6)

Km^{-1}		Size range: diameters in microns				
		0 - 1.25	1.25 - 2.5	2.5 - 5	5 - 10	10 - 20
Waveband	V	3.95	2.50	2.13	2.13	1.91
	W	1.00	2.29	2.72	2.26	2.22
	X	0.34	1.22	2.86	2.32	1.82
	Y	0.03	0.72	2.22	3.14	2.13
	Z	0.00	0.02	0.31	1.10	1.88

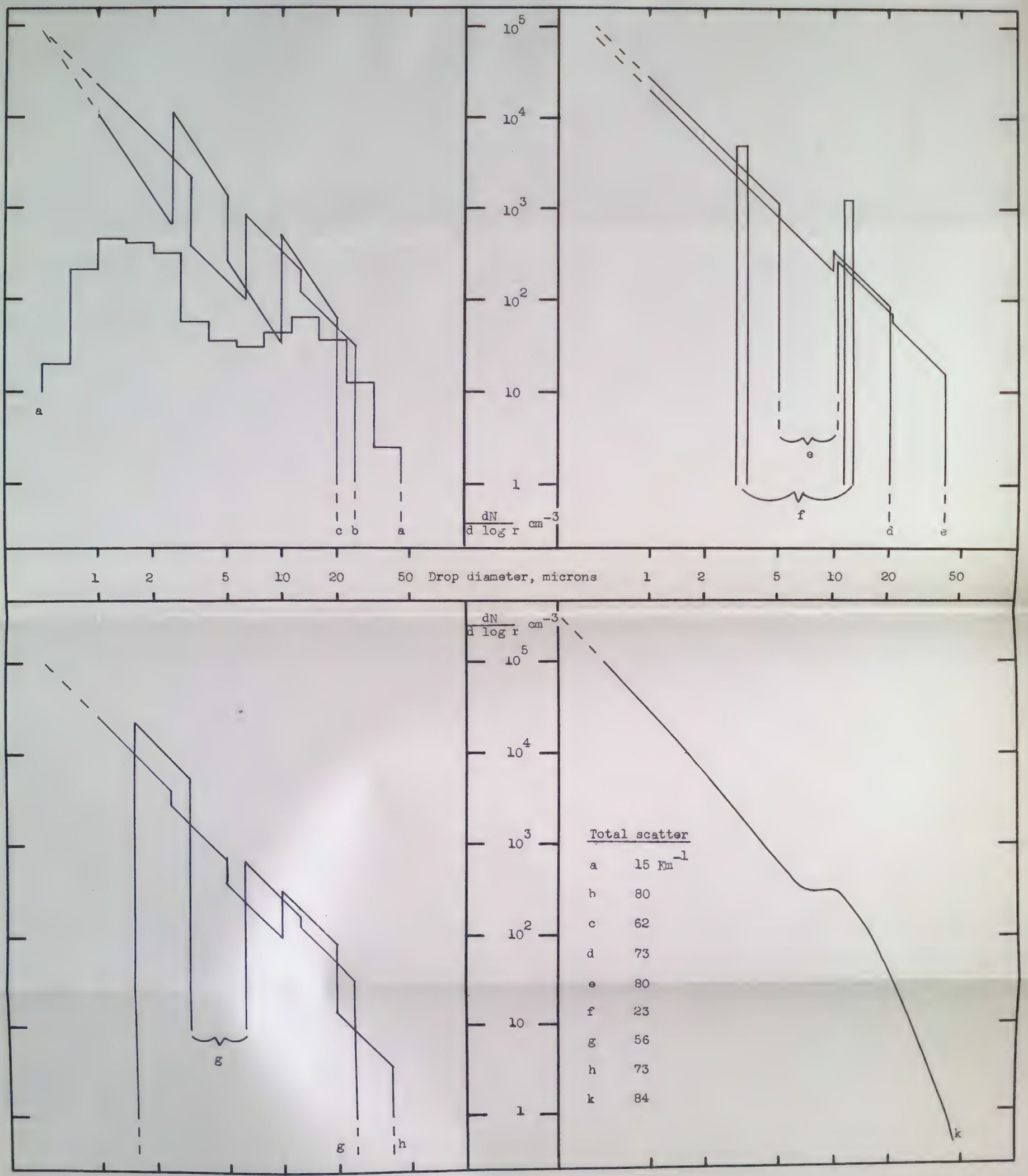

Fig. 1. Drop size distributions for 2130 on 13.11.56

a - cascade impactor results; b–h - various distributions giving results in agreement with scattered light observations, k - final "best estimate" of distribution. Figures on last diagram give calculated total scatter (Km^{-1}) for the various distributions; observed total scatter (i.e. attenuation) was 71 Km^{-1}.

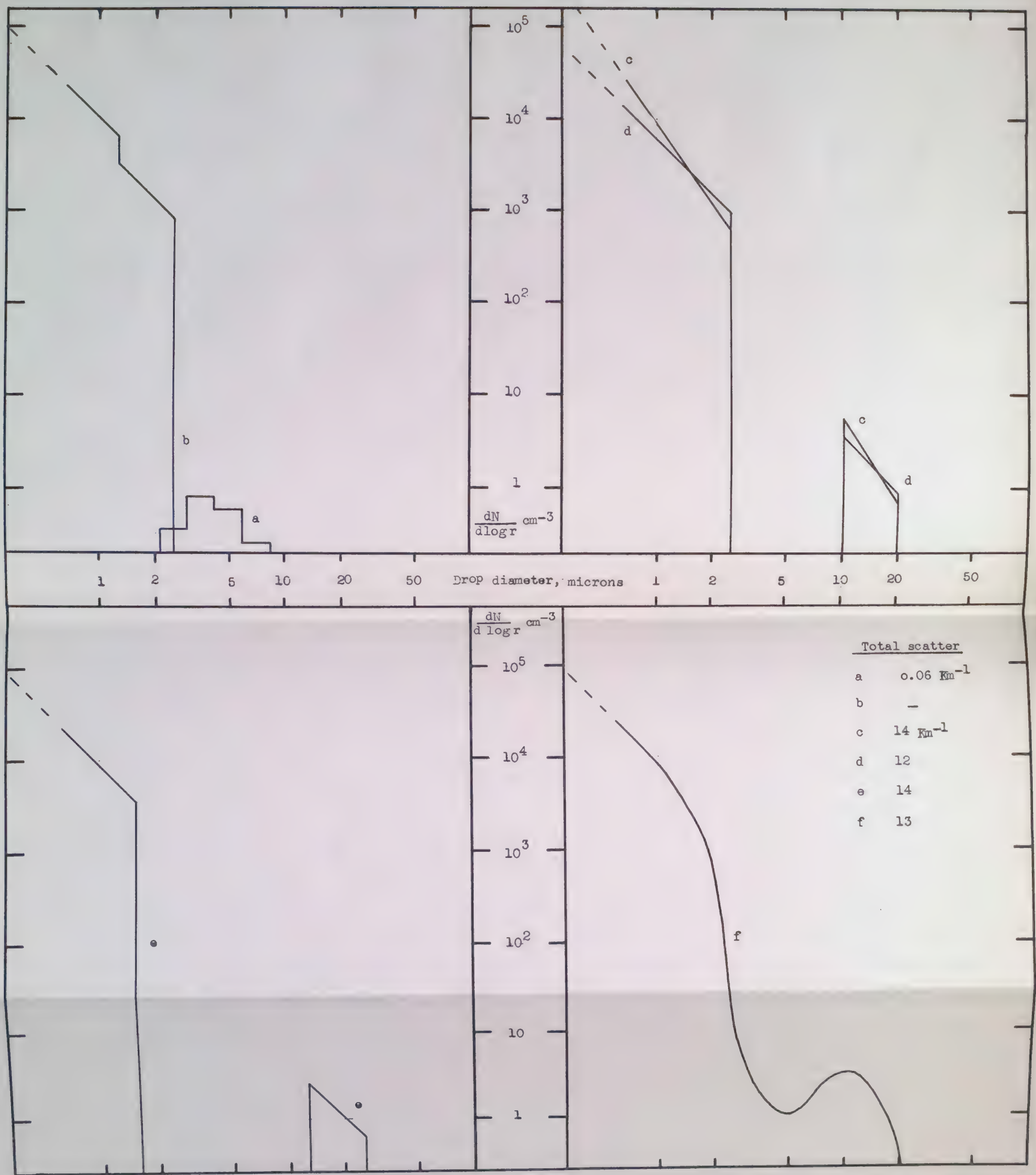

Fig. 2. Drop size distributions for 2320 on 20.12.56 . a – cascade impactor results: b – distribution fitting attenuation observations: c,d,e, – distributions fitting scattered light observations: f – final "best estimate" of distribution. Figures on the last diagram give calculated total scatter (Km^{-1}) for the various distributions; observed total scatter (i.e. attenuation coefficient for visible light) was 12 Km^{-1}.

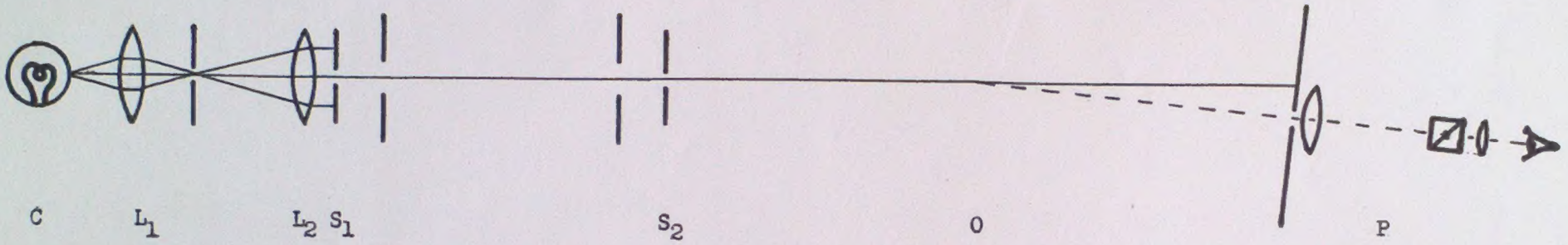

Fig. 3. Schematic diagram of apparatus used for the measurement of scattered light

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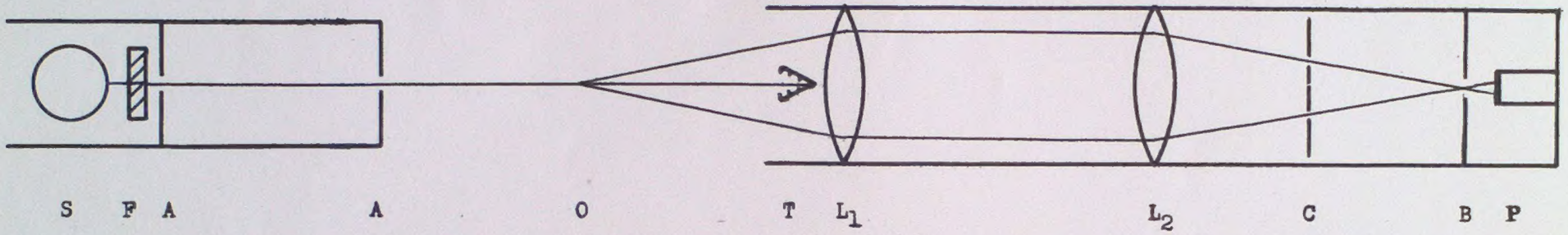

Fig. 4. Schematic diagram of proposed apparatus for measurement of scattered light

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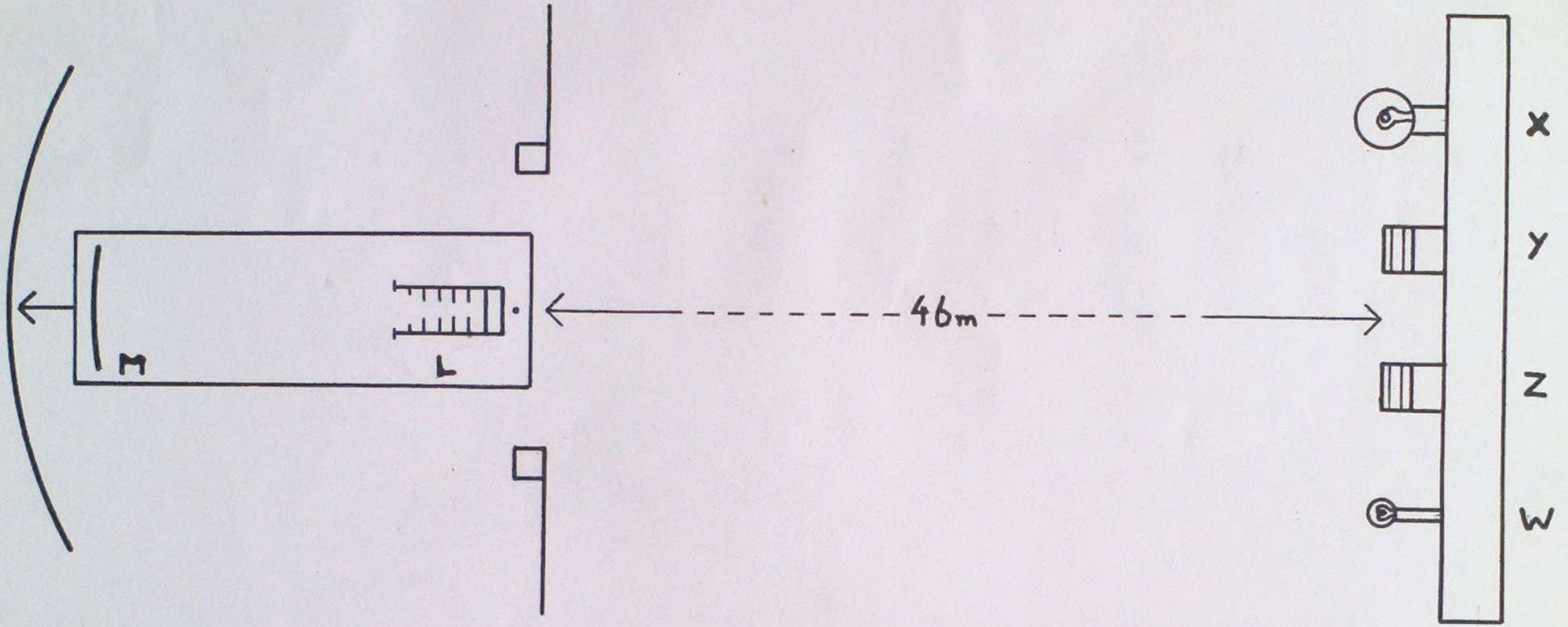

Fig. 5. Schematic diagram of apparatus for measurement of attenuation

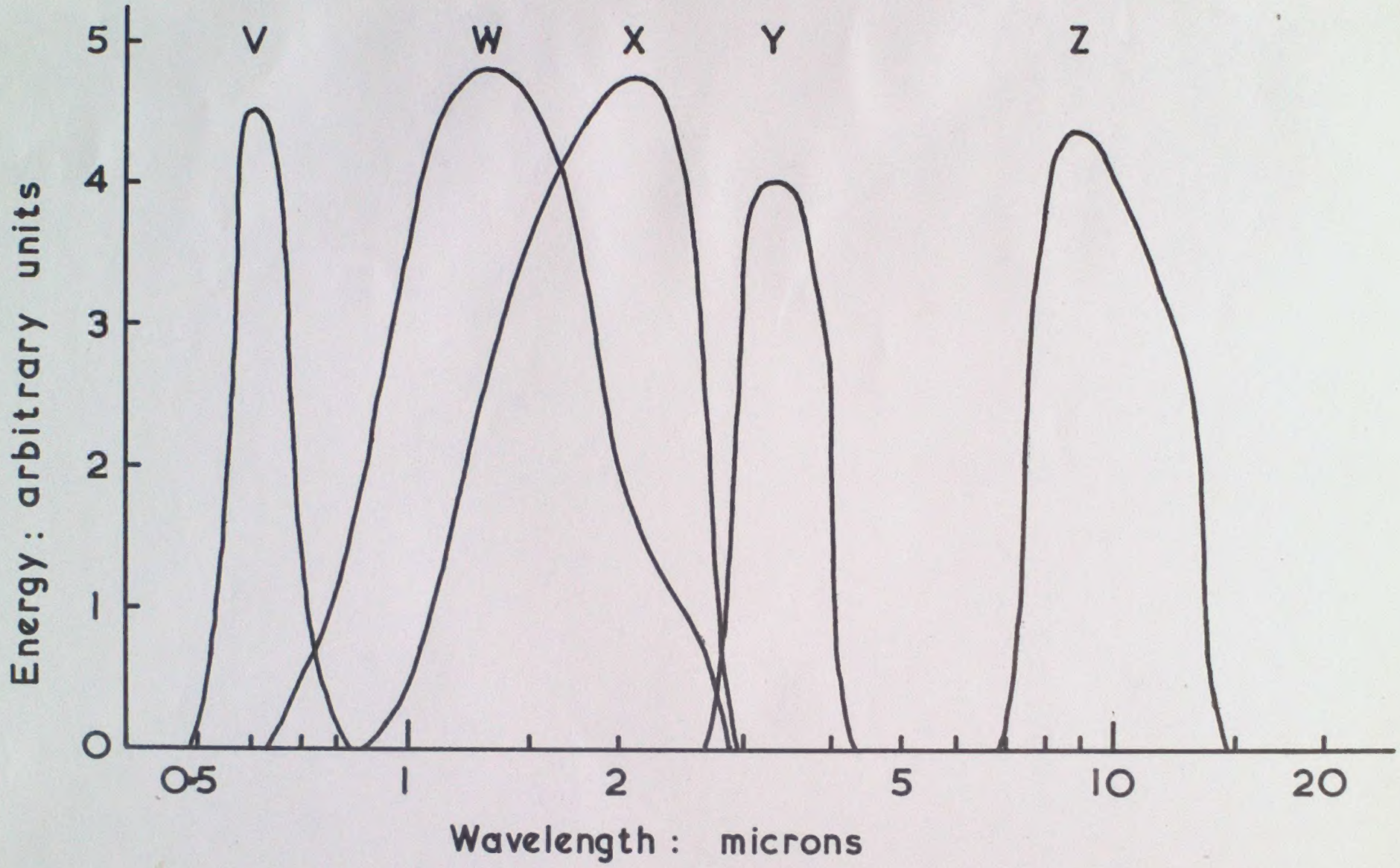

Fig. 6. Effective distribution of energy in wavebands used for attenuation measurements.

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